

Potential impacts of climate change on extreme precipitation over four African coastal cities

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Abstract This study examines the impacts of climate change on characteristics of extreme precipitation events over four African coastal cities (Cape Town, Maputo, Lagos and Port Said) under two future climate scenarios (RCP4.5 and RCP8.5). Fourteen indices were used to characterise extreme precipitation and 16 multi-model simulation datasets from the Coordinated Regional Climate Downscaling Experiment (CORDEX) were analysed. The capability of the models to reproduce past characteristics of extreme precipitation over the cities was evaluated against four satellite datasets after quantifying the observation uncertainties over the cities. The models give realistic simulation of extreme precipitation characteristics over the cities, and in most cases, the magnitudes of the simulation biases are within the observation uncertainties. For

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both the RCP4.5 and RCP8.5 scenarios, the models project a decrease in wet days and an increase in dry spells over the four cities in the future. More intense daily precipitation is projected over Maputo, Lagos and Port Said. The intensity and frequency of extreme precipitation events are projected to increase over Lagos, but decrease over the other cities. A decrease in annual precipitation is projected over Cape Town, Maputo and Port Said, whilst an increase is projected over Lagos, where the water surplus from the more extreme precipitation events exceeds the deficit from the less wet days. A decrease in the number of widespread extreme events is indicated over all the cities. Wet-day percentile and all-day percentile methods signal opposite future changes in the extreme precipitation thresholds over the cities (except over Lagos). The results of this study may have application in managing the vulnerabilities of these coastal cities to extreme precipitation events under climate change.

Keywords Extreme precipitation · Climate change · Regional climate models · African coastal cities

1 Introduction

Extreme weather events remain a threat to socio-economic activities in many coastal cities in Africa because the majority of these cities lack the infrastructure to withstand extreme weather conditions. Extreme precipitation events may cause floods, induce coastal inundation, stress water resource, damage infrastructure, displace communities and destroy human lives. For example, in the Western Cape (South Africa), extreme precipitation event induced floods killed about 100 people and caused more than \$10 million in damages in January 1981 (Estie 1981; Roberts and Alexander 1982). In the same area, more than \$2.5 billion damages were attributed to severe floods from extreme precipitation events between 2003 and 2008 (Holloway et al. 2010). African mega-cities are not only the hub of socio-economic development but are also a vast agglomeration of population. All indications are that the future population growth and advancement in socio-economic infrastructure in Africa will continue to be concentrated in the coastal cities (Adegoke and Ibe 2014). Meanwhile, several studies have documented increasing trends in the intensity and frequency of extreme precipitation events in different parts of Africa and have attributed the trends to climate change (Kruger 2006; Zhang et al. 2007). Therefore, there is a concern that as more people migrate to these cities and climate change continues to increase the intensity and frequency of storms, the loss of lives and economic damages from extreme precipitation events in coastal cities might escalate in the future. The need to mitigate impacts of these events has led to many recent projects and research efforts such as the Climate Change Adaptation for African Coastal Cities project (2C2A2C; Adegoke and Ibe 2014) and the Future Residence For African Cities (FRACTAL; <http://www.fractal.org.za/>), all seeking to influence policy making towards addressing the problem. However, there is a dearth of actionable information on how and at what rate climate change may alter the characteristics of extreme precipitation over the African coastal cities in the future.

Many studies have projected that climate change would continue to modify the characteristics of extreme weather and climate events over Africa (e.g. Mason and Joubert 1997; Shongwe et al. 2009; Oguntunde and Abiodun 2013). For example, using an ensemble of global climate models (GCMs), Mason and Joubert (1997) projected an increase in the intensity of extreme rainfall over the entire southern Africa. Shongwe et al. (2009) also projected an increase in the intensity of dry extremes over the western part of southern Africa during summer months (December-January-February) for the periods of 2046–2065 and 2081–2100. However, the spatial resolution of GCM simulations

used for these projections are too low to resolve the influence of the African complex topography on the atmospheric systems (e.g. mesoscale and synoptic-scale features) that induce extreme precipitation over the continent. To overcome this weakness, some studies have used regional climate models (RCMs) to downscale the GCM projections over the continent (e.g. Engelbrecht et al. 2009; Laprise et al. 2013). However, whilst many studies have used RCM simulations to discuss changes in the long-term averages of rainfall and temperature over Africa, only few of them have investigated the impacts of the climate change on extreme precipitation events. Moreover, the majority of such studies used only single RCM to downscale the GCM simulations (e.g. Engelbrecht et al. 2013, 2015; Dosio and Panitz 2016). For a better sampling of uncertainty associated with future climate projections, there is a need for multi-RCM downscaling of GCM simulations (Hewitson et al. 2013). The Coordinated Regional Climate Downscaling Experiment (CORDEX; Nikulin et al. 2012) has recently provided a step-forward in this regard, by coordinating a multi-RCM downscaling experiment and making the data available publicly. Despite this effort, only few studies have to date utilised the CORDEX dataset in providing multi-RCM future projections on extreme precipitation (Pinto et al. 2016) and heat waves (Lelieveld et al. 2016; Russo et al. 2016) events in Africa, and the study on extreme precipitation events (Pinto et al. 2016) focussed on southern Africa. However, there is need for more studies to target multi-RCM projections on extreme precipitation over the African coastal cities, because such specific information is more relevant for decision making over the cities than broad information at the sub-continent level.

It may also be noted that Pinto et al. (2016) used the wet-day percentile method in projecting a decrease in wet days and an increase in precipitation intensity over some parts of southern Africa. However, Schär et al. (2016) have cautioned against the use of the wet-day percentile method in projections of extreme precipitation thresholds. They found, in their GCM projections, that the method produced an artificial increase in the threshold over some parts of South Africa due to a substantial decrease in wet days over the region. Hence, they recommended the use of an all-day percentile method instead of the wet-day percentile method. It is therefore of interest to compare the results of the two methods over the four cities in the multi-RCM simulations. In addition, the emphasis of Pinto et al. (2016) was on grid point extreme precipitation events rather than on occurrence of widespread flood-inducing precipitation events. Meanwhile, a widespread extreme precipitation event from a mesoscale or synoptic feature may induce more devastating floods over a city or river basin than that of a localised extreme precipitation event. Whilst Abiodun et al. (2015) have demonstrated the capability of CORDEX simulations in reproducing the characteristics of widespread extreme precipitation event (WERE) over the Western Cape, till date, no studies have shown how climate change could alter the characteristics of WERE over African coastal cities in the future.

Therefore, the aim of the present study is to examine the potential impacts of climate change on characteristics of extreme precipitation events over four major coastal cities in Africa (Cape Town, Maputo, Lagos, and Port Said) using CORDEX multi-model simulations. Section 2 describes the data and methods used in the study, Sect. 3 presents the results and discussion, whilst Sect. 4 gives the concluding remarks.

2 Methodology

2.1 Study areas

This study focuses on small areas surrounding the four African coastal cities (Cape Town, Maputo, Lagos, and Port Said; Fig. 1). Cape Town and Port Said are located in the

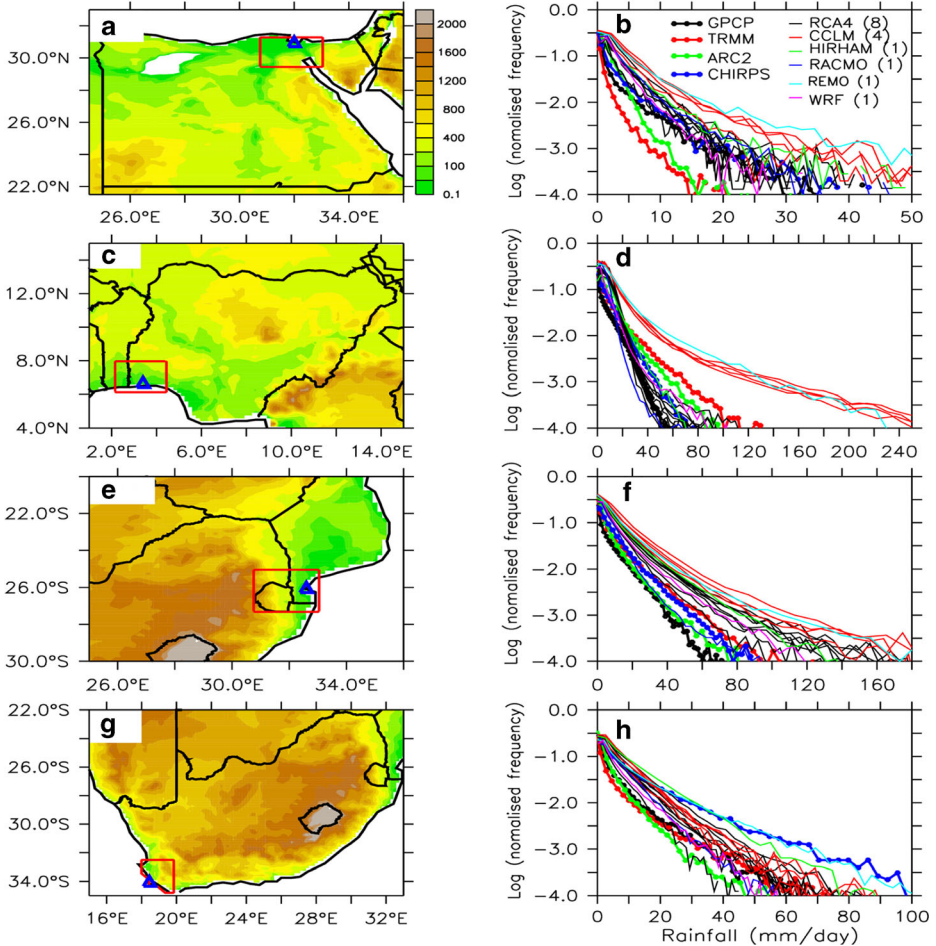


Fig. 1 Topography and precipitation intensity in the neighbourhood of the four coastal cities. The *left panels* (a, c, d, f, respectively) show the location (Δ) of each city (Port Said, Lagos, Maputo and Cape Town, respectively) and the region (*red contour*) designated as the city's neighbourhood (or area). The *right panels* (b, d, f) show the corresponding precipitation intensity-frequency curves for the past climate, as observed (GPCP, TRMM, ARC2 and CHIRPS) and simulated (multi-model simulations from six RCMs: RCA, CCLM, HIRLAM, RACMO, and REMO and WRF). The number of simulations from each RCM is indicated in *bracket*

Mediterranean climate zone (Northern and Southern Hemisphere, respectively), whilst Lagos and Maputo are located in the tropical climate zone (Northern and Southern Hemisphere, respectively). Although the four cities are located in different climatic regions, they are selected for this study because they are good representatives of other African coastal cities and are important for sustainable development in their respective countries and in Africa. In addition, they are the objects of many climate change mitigation projects such as 2C2A2C and FRACTAL.

Cape Town (33.9°S, 18.9°E) is the tenth most populous city in Africa, the most popular tourist city in Africa, and one of the most prominent multi-cultural cities in the world.¹ The city

¹ <http://www.expatcapetown.com/why-cape-town.html>

experiences a mild to moderately wet winter (June–August) and dry warm summer (December–March) (Robinson and Henderson-Sellers 1999). The temperature of Cape Town ranges from 8 to 18 °C in winter months and from 16 to 26 °C in summer months. The annual precipitation in Cape Town is about 515 mm and most of the precipitation is from cold front with northwesterly winds. Maputo (25.9°S, 32.6°E) is the largest and southernmost city of Mozambique. It has a tropical climate with relatively colder dry winter (May–October) and warm wet summer (November–April). In Maputo, the average maximum temperature varies from 25 to 30 °C in summer and the average minimum temperature ranges from 14 to 20 °C (Tadros and Johnson 2012). The total annual rainfall is about 800 mm. Lagos (6.5°N, 3.4°E) is the industrial and economic hub of Nigeria, the most populous city in Africa and one of the fastest growing cities in the world (Ibe 1989). Lagos has a tropical wet and dry climate, with temperature that ranges from 14 to 37.0 °C. The city has wet and dry seasons. The wet season, which is characterised by moist southwest winds (monsoon) from Atlantic Ocean, features the heaviest rains from April to July, a short dry spell in August, and rains in October and November (Omotosho 1988; Abiodun et al. 2013). The dry season (December to February) is characterised by dry northeast trade wind (Harmattan) from the Sahara desert. Port Said is the second most populous city in Egypt and a popular tourist resort (El Raey 2009). This city experiences a hot desert climate, but the blowing wind from the Mediterranean Sea moderates the climate (Robinson and Henderson-Sellers 1999). The temperature of Port Said ranges from 0 °C in December to 44 °C in June. The summer is moderately hot and humid, and the winter is wet, featuring sleet and hail.

2.2 Data

The simulated daily rainfall data from the CORDEX simulation dataset were analysed for the study. The simulations were produced by six of the CORDEX RCMs (RCA4, CCLM, HIRLAM, RACMO, REMO and WRF) used in downscaling GCM simulations for past climate (1986–2005) and future climate (2046–2065 and 2081–2100) under the RCP4.5 and RCP8.5 scenarios (i.e. the middle- and high-level emission scenarios, respectively). For detailed information on the models and their configuration for the CORDEX experiment, readers are referred to Nikulin et al. (2012). Whilst RCA downscaled eight GCM simulations (CCCMA, CNRM, GFDL, HADGEM, ICHEC, MIROC, MPI and NCCN), CCLM downscaled four (CNRM, HADGEM, ICHEC and MPI), HIRLAM downscaled ICHEC, RACMO downscaled ICHEC and REMO downscaled MPI. The information of the GCM simulations is given in the auxiliary materials. All RCM simulations were performed at a grid resolution of $0.44^\circ \times 0.44^\circ$ over the same Africa domain (Nikulin et al. 2012).

Four gridded satellite rainfall datasets were used to evaluate the CORDEX simulations. The first observation dataset is the Global Precipitation Climatology Project (GPCP, version 1.1). GPCP produces daily precipitation data at a spatial resolution of $1^\circ \times 1^\circ$ using a combination of geosynchronous satellite infrared readings and low earth polar orbit satellite observations (Huffman et al. 2001). The second dataset is the Tropical Precipitation Measurement Mission (TRMM 3B-42, version 6, hereafter TRMM; Huffman et al. 2007). TRMM produces 3-hourly precipitation data at $0.25^\circ \times 0.25^\circ$ spatial resolution using merged microwave infrared estimates such as the TRMM microwave imager (TMI), the visible infrared scanner (VIRS) and the TRMM precipitation radar. The third dataset is the Climate Prediction Centre (CPC) Africa Rainfall Climatology version 2.0 (ARC2; Novella and Thiaw 2013). ARC2 consists of daily precipitation estimations data at 0.1×0.1 spatial resolution using the 3-hourly

geostationary infrared (IR) data from the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), and the quality-controlled Global Telecommunication System (GTS) gauge observations reporting 24-h rainfall accumulations over Africa. The fourth data is the Climate Hazards group Infrared Precipitation with Stations (CHIRPS; Funk et al. 2015). CHIRPS incorporates $0.05^\circ \times 0.05^\circ$ resolution satellite imagery with in situ station data to create gridded rainfall time series for trend analysis and seasonal drought monitoring. We used these four observation datasets to address the issue of observation uncertainty over the cities.

2.3 Method

Fourteen indices were used in characterising extreme precipitation over the cities. The definitions of these indices are given in Table 1. Ten of the indices are from the Expert Team on Climate Change Detection and Indices (ETCCDI) whilst the others are slight modifications of the ETCCDI indices. Eight of the indices quantify the intensity of extreme precipitation events (mean and strong; Table 1a), four consider the frequency (Table 1b), and two measure the duration (Table 1c). Fixed and percentile values were used as the threshold of the extreme precipitation events; the percentile values were calculated using both the wet-day percentile (i.e. RW95p) and the all-day percentile (i.e. RA95p) methods (Table 1). However, it should be noted that the ETCCDI indices only characterise moderate extreme events (Klein Tank et al. 2009). We focus on these moderate extreme events instead of the rare extreme events (of the Generalised Extreme Value Theory (GEVT); Coles 2001), because Pinto et al. (2016) found that the CORDEX RCMs do not capture well the rare extreme events over southern Africa. In addition, since the moderate extreme events occur at least once per year, their results are more robust than that of rare extreme events. For each dataset (observation and simulation), the indices were calculated and averaged over the grid points within the neighbourhood of each city (Fig. 1). The simulated indices were calculated over the CORDEX common grid ($0.44^\circ \times 0.44^\circ$), but the observed indices were calculated over the native grid of each observation dataset as suggested by Diaconescu et al. (2015). However, both observed and simulated precipitation intensity-frequency analyses were performed over the CORDEX common grid.

3 Results and discussion

3.1 Model evaluation over the cities

Before discussing the CORDEX model projections of future changes in extreme precipitation, it is essential to evaluate the performance of the models over the cities, because our confidence in any model projection depends on the capability of the model to reproduce the past climate. Hence, in this section, we evaluate the model's performance by comparing the simulated precipitation characteristics with observed characteristics over the cities. However, to put the model performance in the right perspective, we first quantify the observation uncertainties and then compare the model biases with the uncertainties.

In general, the observation datasets (GPCP, TRMM, ARC2 and CHIRPS) show a good agreement on the characteristic of precipitation over the cities, but there are some notable differences (Figs. 1 and 2). For instance, in the precipitation intensity-frequency curve (Fig. 1),

Table 1 The definitions of the extreme precipitation indices used in the study and the projected changes in the indices over the cities (*CPTA* Cape Town, *MPTA* Maputo, *LGSA* Lagos and *PTSA* Port Said) in 2081–2100 under RCP4.5 and RCP8.5 scenarios (first and second symbols, respectively)

Indices	Definition	CPTA	MPTA	LGSA	PTSA
(a) Mean and strong intensity indices					
WDays ^a	Wet days. Annual count of days with daily precipitation greater or equal to 1 mm	↓↓	↓↓	↓↓	↓↓
PRCPTOT ^a	Annual total precipitation in wet days	↓↓	↓↓	↑↑	↓↓
SDII ^a	Simple precipitation intensity index	↑↓	↑↑	↑↑	↑↑
RW95p ^a	Wet-day percentile. The 95th percentile of precipitation on wet days	↑↑	↑↑	↑↑	↑↑
RA97.5p	All-day percentile. The 97.5th percentile of precipitation on all days (i.e. wet days and dry days) (Schär et al. 2016)	↓↓	↓↓	↑↑	↓↓
R95pTOT ^a	Annual total precipitation when daily rainfall is greater than or equal to RW95p	↓↓	↑↓	↑↑	↑↓
R97.5pTOT	Annual total precipitation when daily rainfall is greater than or equal to RA97.5p (Schär et al. 2016)	↓↓	↑↑	↑↑	↓↓
Rx5Days	Maximum consecutive 5-day precipitation	↓0	↑↑	↑↑	↑↑
(b) Occurrence indices					
R20mm ^a	Annual count of days when daily rainfall is greater or equal to 20 mm	0↓	↓↓	↑↑	↑↑
RW95pFREQ ^a	Annual count of days when daily rainfall is greater or equal to RA95p of the present-day climate (Schär et al. 2016)	0↓	↑↓	↑↑	↓↓
RW9.75pFREQ	Annual count of days when daily rainfall is greater or equal to RA97.5p of the present-day climate	↓↓	↓↓	↑↑	↓↓
WERE	Widespread extreme rainfall event. Annual count of days when daily rainfall is greater or equal to RA97.5p (of the present-day climate) simultaneously over 50% of the area of interest. WERE helps retain extreme precipitation events induced by mesoscale of synoptic scale features (Abiodun et al. 2015)	↓↓	↓↓	↓↓	↓↓
(c) Duration indices					
CDD ^a	Maximum length of dry spell. Maximum number of consecutive days with daily precipitation less than 1 mm	↑↑	↑↑	↑↑	↑↑
CWD ^a	Maximum length of wet spell. Maximum number of consecutive days with daily precipitation greater than 1 mm	↑↓	↑↓	↑↓	0↓

Upwards arrow depicts an increase, downwards arrow depicts a decrease and zero depicts no change. The references for other definitions are indicated in the table. The projections are the CORDEX simulation median

^a The ETCCDI climate change indices (Klein Tank et al. 2009)

the observation datasets cluster together over Maputo (Fig. 1f) but diverge over the other cities (Fig. 1b, d, h). CHIPRS produces a curve with the longest tail (i.e. highest number of heavy precipitation events) over Cape Town. TRMM that produces a curve with the longest tail over Lagos and features the one with the shortest tail over Port Said. Meanwhile, GPCP and ARC2 have curves with the shortest tail over Lagos, but curves with the longest tail over Port Said. Furthermore, the uncertainty in the observed annual wet days (WDays) is up to 37 days over Cape Town and Maputo, 48 days over Lagos and 12 days over Port Said, whilst that of annual precipitation (PRCPTOT) is up 120 mm over Cape Town, 390 mm over Maputo, 350 mm over Lagos and 23 mm over Port Said. However, whilst GPCP consistently reports the highest WDays over the cities, TRMM reports the highest simple precipitation intensity index (SDII) and extreme precipitation threshold (RA97.5p and RW95p), intensity (RA7.5pTOT, RW95pTOT and Rx5Days) and frequency (R20mm) over Cape Town, Maputo and Port Said.

This implies that, over these cities (Cape Town, Maputo and Lagos), TRMM reports fewer but more intense precipitation events than what GPCP reports. However, GPCP features more intense and more frequent precipitation event than TRMM over Port Said. In addition, it produces the highest number of WEREs over the four cities. Several studies (e.g. Sylla et al. 2013; Abiodun et al. 2011, 2015) have also reported similar discrepancies (especially, between TRMM and GPCP) over various parts of Africa and attributed the discrepancies to the difference in resolutions of the datasets. However, the impacts of observation uncertainty on model development and evaluation call for more studies on how to reduce the observation uncertainty over Africa.

The CORDEX models give realistic simulations of precipitation characteristics over the cities, and in some cases, the simulations spread is within the observation uncertainty (Figs. 1 and 2). For example, over Cape Town, all the simulated precipitation intensity-frequency curves cluster around the TRMM and GPCP curves and fall between ARC2 and CHIRPS curves. Almost all the simulated SDII, RW95p, CDD, RA97.5pTOT and Rx5days fall within the observed values. Although the spread of the simulated RA97.5p, RW95pTOT and R20mm

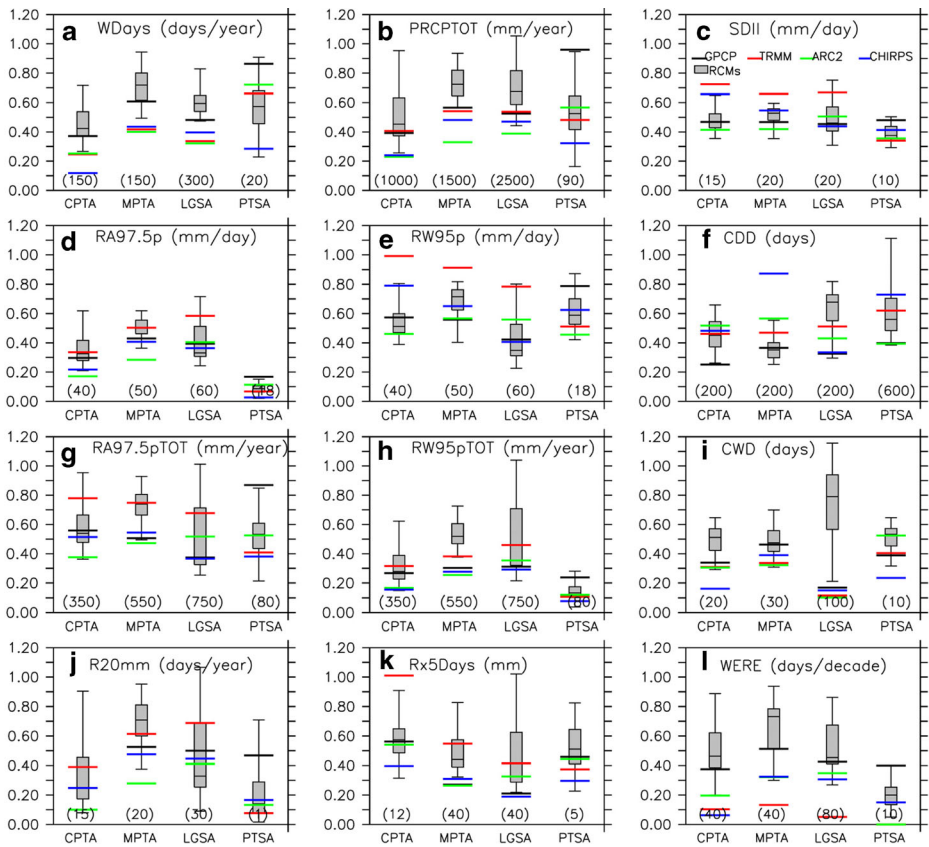


Fig. 2 The climatology of extreme precipitation indices over each city (CPTA Cape Town, MPTA Maputo, LGSA Lagos, PTSA Port Said) in the past climate, as observed (ARC2, GPCP and TRMM) and simulated (multi-ensemble simulations from six RCMs). For each city, the values are averaged over the city’s neighbourhood (shown in Fig. 1) and normalised with the number in bracket. To obtain the actual values, the indicated values should be multiplied with the number in bracket for the city. The descriptions of the variables are in Table 1

is wider than observation, the simulations median is still within the observed values. However, most simulations overestimate PRCPTOT, possibly because they overestimate WDays, wet spell (CWD) and frequency of WEREs. The model's performance over the other cities is similar to that of Cape Town, except that, in the precipitation intensity-frequency curves, most simulations cluster around GPCP and CHIRPS over Port Said, few overestimate the tail of the curve over Lagos and most overestimate it over Maputo. This overestimation (i.e. too frequent heavy precipitation events) and that of WERE suggest that the models exaggerate the convective available potential energy (CAPE) of boundary air or produce too strong moisture flux convergence over the cities. Nevertheless, the models perform best over Port Said (where most of the simulated indices are within the observed) and perform worst over Maputo and Lagos. The best performance of the models over Port Said may be due to low precipitation over this city.

The simulations and observations indicate that the results from all-day percentile and wet-day percentile methods differ (i.e. RA97.5p versus RW95p and RA97.5pTOT versus RW95p; Fig. 2). The closest agreement between the methods occurs over Lagos. Over other cities, RW95p is higher than RA97.5p; hence, RW95pTOT is lower than RA97.5pTOT. This difference contradicts the augment of Schär et al. (2016) that RW95p and RA97.5p should give almost the same values. The contradiction may be because Schär et al. (2016) result is based on grid-point data whilst ours is based on area-averaged data. It may also be that the results of the two methods are sensitive to the wet-day fraction in the datasets. To find the closest value of all-day percentile to the RW95p, we computed the 98th, 98.5th, 99th and 99.5th percentiles (RA98p, RA98.5p, RA99p and RA99.5p) using the all-day percentile method. The results indicate that the closest value to RW95p is RA99.5p over Cape Town, RA98.5p over Maputo, RA98p over Lagos and RA99.5p over Port Said (see auxiliary materials). However, for consistency, we used RA97.5p for future projection over all the cities; the RA97.5p projection is consistent with those obtained with the higher percentiles (see auxiliary materials).

3.2 Future projections over the cities

3.2.1 Cape Town

Figure 3a presents the projected future changes in extreme precipitation indices over Cape Town, using the inter-quartile simulations spread (i.e. box plot) to indicate the agreement amongst the simulations on the projections. Most simulations (at least 75%) project a decrease in WDays and PRCPTOT over the city, under both the RCP4.5 and RCP8.5 scenarios. The ensemble median indicates a decrease of about -10% (RCP4.5) and -15% (RCP8.5) in 2081–2100. Whilst the magnitude of the decrease remains constant with time under RCP4.5 scenario, it increases over time under RCP8.5 scenario. Owing to the commensurate decrease in these two indices, there is no substantial change in SDII (the ensemble median is $\pm 3\%$), and there is a poor agreement amongst simulations on the direction of the change. Nevertheless, most simulations project a decrease in the intensity and frequency of extreme precipitation (i.e. RA97.5p, RA97.5pTOT, RA95pFREQ and WERE) over the city. Hence, the decrease in PRCPTOT can be attributed to the decrease in both WDays and extreme precipitation events. However, wet-day percentile and all-day percentile methods signal opposite changes in extreme precipitation threshold over Cape Town. For example, in 2081–2100, whilst RA97.5p indicates a decrease, RW95p depicts an increase. The increase in RW95p may be an artefact of the decrease in WDays. Schär et al. (2016) found a similar discrepancy

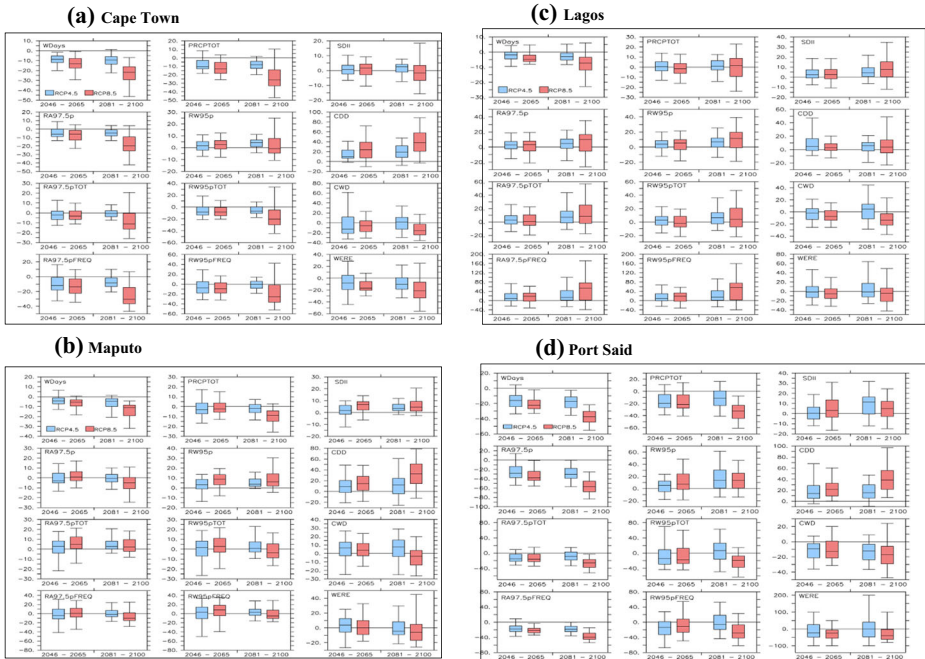


Fig. 3 Projected percentage changes in extreme precipitation indices over the four cities (**a** Cape Town, **b** Maputo, **c** Lagos and **d** Port Said) in the two future periods (2046–2065 and 2081–2100) under RCP4.5 and RCP8.5 scenarios. The changes are calculated with reference to the past climate (1986–2005) and are averaged over the neighbourhood of the city (shown in Fig. 1)

between the two percentile methods in GCM projections over South Africa and attributed the artificial increase in wet-day percentile to a substantial decrease in the wet-day fraction. Nonetheless, the two methods agree on changes in other indices (i.e. RW95pTOT versus RA97.5pTOT and RW95pTOT versus RA97.5pTOT). The projected increase in the length of dry spell (CDD) and decrease in the length of wet spell (CWD) are in line with the decrease in WDays. The direction of changes in all these indices (i.e. CDD, PRCPTOT, RW95pTOT and SDII) are consistent with those obtained by Pinto et al. (2016) over Western Cape, except that the magnitudes of the projection differ due to the difference in size of the study area and in the number of simulations used in the studies. These findings are largely consistent with the notion that frontal rainfall (and related extreme events) may decrease over the Western Cape under climate change due to the poleward displacement of mid-latitude storm tracks (e.g. Engelbrecht et al. 2009).

3.2.2 Maputo

A decrease in both WDays and PRCPTOT is also projected over Maputo, except that there is a better agreement amongst the simulations on the WDays projection than on the PRCPTOT projection (Fig. 3b). However, more than 75% of the simulations agree on the decrease in both WDays and PRCPTOT in 2081–2100 under RCP8.5 scenario. Unlike over Cape Town, the projected decrease in WDays outweighs that of PRCPTOT; therefore, an increase in SDII is projected over Maputo. This implies that the future normal precipitation may be more intense than the past. With the all-day percentile method, the extreme precipitation threshold

(RA97.5p) and frequency (RA97.5pFREQ) are projected to be lower, but with higher total precipitation amounts from the extreme events (RA97.5pTOT). On the contrary, the wet-day method indicates an increase in the extreme precipitation threshold (RW95p) due to the substantial decrease in WDays. Most simulations indicate an increase in duration of dry spells, but there is no agreement amongst the simulations in terms of the direction of changes in wet spells. However, in 2081–2100, the ensemble median indicates an increase in the wet spell under RCP4.5 but a decrease under RCP8.5. These findings are largely consistent with the notion that the summer rainfall regions of southern Africa may become generally drier with more frequent dry spells under climate change, in response to the strengthening of anti-cyclonic circulation (e.g. Engelbrecht et al. 2009) and an equatorward displacement of tropical low tracks (Malherbe et al. 2013).

3.2.3 Lagos

Most of the simulations also project a decrease in WDays but an increase in PRCTOT over Lagos, especially in 2081–2100 under both RCP4.5 and RCP8.5 scenarios (Fig. 3c). Hence, an increase in SDII is projected over the city, depicting an intensification of normal precipitation in the future. This finding is consistent with the general correspondence in GCM projections that extreme precipitation events over West Africa may increase under climate change (e.g. Haensler et al. 2013), although the confidence in these projections is relatively low (e.g. compared to the projections over southern Africa). Interestingly, all-day and wet-day percentile methods agree over Lagos. For both methods, an increase in extreme precipitation intensity (e.g. RW95p, RA97.5p and RA97.5pTOT) and frequency (e.g. RW95FREQ and R20mm) is also projected over the city. However, WEREs are projected to decrease. This implies an increase in the frequency of storms generated by local scale features, but a decrease in those from synoptic-scale or large-mesoscale systems. Consistent with the decrease in WDays, an increase in CDD is also projected for both RCP4.5 and RCP8.5, but no consensus is reached amongst the simulations on future changes in CWD.

3.2.4 Port Said

For Port Said, a decrease in both WDays and PRCTOT is projected but with a higher SDII (Fig. 3d). Despite the increase in SDII, a decrease in extreme precipitation intensity and frequency is projected over the city. The disparity between all-day and wet-day percentile methods on extreme precipitation threshold is most visible over Port Said, possibly because the decrease in WDays is most substantial over Port Said. For instance, whilst RW95p suggests an increase (up to +60%) in extreme precipitation threshold, RA97.5p indicates a decrease (up to +15%). But, despite the disparity, both methods agree on the direction of change in extreme precipitation frequency (RW95pFREQ and RA97.5pFREQ) and in amount of precipitation from the extreme precipitation events.

Thus, a major projection that cut across the four cities is a decrease in WDays with an increase in CDD. At least for the cases of Lagos and Maputo, where rainfall is predominantly convective, this is consistent with the conceptual ideal that anthropogenic warming may increase the capacity of the atmosphere to contain more water. Such a warmer atmosphere may plausibly require more time (days) to reach saturation and produce precipitation. However, such a saturated but warmer atmosphere may consistently be associated with an increase

in the SDII (as projected over three cities) due to increase in moisture content (compared to the past climate). For the case of Cape Town and Port Said, it is more likely that the mechanisms related to the projected changes in extremes are to be found in the displacement and movement of mid-latitude weather systems (this aspect requires further research and is beyond the scope of this paper). An increase in the frequency of extreme precipitation is projected over Lagos whilst a decrease is projected over the other cities (Cape Town, Maputo and Port Said). This disparity may be due to the differences in atmospheric systems that induce extreme events over these cities. For example, over Cape Town, the extreme precipitation is usually from frontal systems (including cutoff lows). Anthropogenic warming might decrease the CAPE of boundary layer air over the continent, thereby suppressing the occurrence of deep convections. Over Lagos, on the other hand, the extreme precipitation is usually induced by localised thunderstorms or mesoscale convective systems, using moisture from the moist air mass from the adjacent warm tropical Atlantic Ocean. The anthropogenic warming might increase the CAPE of the maritime air, thereby making the storms more intense. Nevertheless, a decrease in WERE is also projected over the cities (including Lagos), because the atmospheric systems that produce WERE require conditionally unstable moist air to cover a large area, but the anthropogenic warming might reduce the area covered by the moist air. This suggests that regional changes in circulation (e.g. enhanced anticyclonic circulation for the case of Maputo) are functioning to reduce the areas covered by moist air. However, whilst the projected increase in the frequency and intensity of extreme precipitation over Lagos suggests more floods in the city, the projected decrease in dry spell over the four cities may reduce agricultural production, strain water resources and compromise food security.

4 Conclusion

As part of efforts to understand the vulnerability of African coastal cities to climate change, this study has investigated the impacts of climate change on extreme precipitation over four coastal cities in Africa (Cape Town, Maputo, Lagos and Port Said). Three observation datasets and 16 CORDEX model simulations (from six RCMs) have been analysed to describe the characteristics of extreme precipitation, quantify observation uncertainty, and evaluate the performance of models in the past climate. The model simulations were used to project future changes in the extreme precipitation under two future mitigation scenarios over the cities. Results of our analysis are summarised as follows:

- Although there are good agreements amongst the observation datasets (RCA4, GPCP and TRMM) on precipitation characteristics over the cities, there are still notable differences.
- CORDEX models give a credible simulation of precipitation characteristics over the cities, and in some cases, the model biases are within the observation uncertainties.
- For both RCP4.5 and RCP8.5, fewer wet days with longer dry spells is projected over the four cities in the future; however, over Maputo, Lagos and Port Said, the intensity of future precipitation may be stronger.
- An increase in annual precipitation and extreme precipitation (frequency and intensity) is projected over Lagos, but a decrease is indicated over the other cities.
- All-day and wet-day percentiles methods signal different results over the cities (except Lagos) because the wet-day percentile produces an artificial increase in extreme precipitation threshold over the cities.

- A decrease in widespread extreme events is projected over Lagos, despite the increase in extreme precipitation. This implies that frequency of local-scale storms may increase whilst that of synoptic-scale or large mesoscale-induced storms may decrease. Hence, local-scale features may play a more crucial role in generating extreme precipitation over Lagos in the future.

To provide more robust information for policymakers on the impact of climate change on extreme rainfall over these four cities, the results of this study can be improved in many ways. For example, the CORDEX simulation dataset has some limitations. The resolution of the simulations is too low to resolve urban heat island, which some studies have shown to be important for extreme precipitation, and it is not clear if the simulations included parameterisations for urban heat island. To address this shortcoming, a desirable resolution and experimental setup for future CORDEX simulations should be similar to that described in Hamdi et al. (2015). Moreover, the CORDEX simulations are not cloud resolving, implying that the projected changes in extreme precipitation are subject to the uncertainties associated with the parameterisation of cumulus convection (e.g. Biasutti et al. 2008). In addition, the future CORDEX should archive the upper level data with which the CAPE and vertical structure of atmospheric systems associated with the extreme precipitation can be analysed. Nevertheless, the present study has demonstrated the capability of CORDEX simulations to reproduce the characteristics of extreme precipitation over the cities and showed how the anthropogenic warming may plausible alter the characteristics in the future.

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